**International Conference on Applied Energy 2019**
**Aug 12-15, 2019, Västerås, Sweden**
**Paper ID:232**

# NUMERICAL INVESTIGATION ON THE EFFECT OF WALL FILM ON SOOT EMISSION IN A DUAL INJECTION GASOLINE ENGINE

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**ABSTRACT**

To explore the particulates formation process of GDI engine, a three-dimensional model of dual injection gasoline engine combined with intake PFI (port fuel injection) and GDI was established. And simulation was carried out to describe the process of spray impingement, mixture formation, combustion, and soot formation inside the cylinder. The results show that, the soot is primarily generated at thick zone of mixture, and increasing the PFI proportion will effectively reduce the film mass and soot emissions. Increasing the PFI proportion to 15% the film peak mass in cylinder decreases 14.3% compare to the film peak mass of 100% GDI strategy, and soot mass fraction decreases 31.1%. Increasing the PFI rate to 35% the peak quality of film in cylinder decreases 40%, soot mass fraction decreases 77%. With GDI spray timing delay, wall film peak mass decreased firstly and then increased, at the same time, soot mass fraction decreased firstly and then increased too. Therefore, adjusting the injection proportion and GDI timing of dual injection engine are effect ways to decrease spray impingement, optimize mixture distribution and improve soot emission.

**Keywords:** equivalence ratio, injection proportion, injection timing, uniformity index

## 1. INTRODUCTION

As a new method to improve GDI particle emission, dual injection engine with PFI and GDI is a hotspot in the research of new generation gasoline engine. Daniel et al. studied the exhaust gas and particulate emission when injecting ethanol gasoline mixture fuel into the intake port and cylinder, and the results showed that compared with direct injection gasoline engine, dual injection gasoline engine could reduce particulate emission and carbon oxide and HC emissions.

Yuan et al. analyzed the effect of injection timing of direct injection in ethanol engine on detonation suppression, and the results showed that spray ethanol after intake valve closing could improve the detonation, but the mixture quality decreased, leading to higher emissions. Francesco et al. made a comparative study on the effects of the dual injection system burning ethanol gasoline and the direct injection of the same proportion of blended fuel on the two fuel supply modes on the engine performance and emissions. The results showed that compared with the direct injection the dual injection system could improve the thermal efficiency of the engine and reduce the particles mass and average diameter, but at the same time the number of nuclear particles increased.

It can be seen from the above research, current researches focus on experiments of particulate emissions on dual injection engine, the particle formation process and the factors affecting particle formation, namely the wall film and the distribution of the mixture in the dual injection engines are still needed to be studied. Especially in the dual injection engine wall film of the soot emission effect research is still blank.

This paper combined the engine bench test with 3D simulation software, systematically studied the GDI and PFI, injection mode, different injection strategies on wall film formation and development process, the influence of the mixture distribution and the soot formation process, focused on the influence of fuel film on the mixture in cylinder uniformity, thick area and soot emission.

## 2. CALIBRATION OF SPRAY MODEL

### *2.1 Spray Characteristics Experiment*

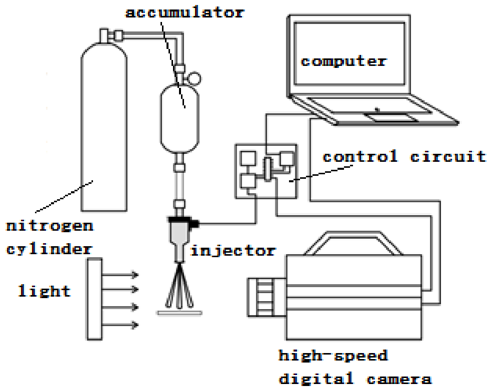


Fig 1 Experimental device of shooting spray

The injector used in experiment is a six holes injector, the injector is set in the head of the constant volume vessel and its central axis is perpendicular to the upper plane of the constant volume vessel. In order to provide accurate boundary condition, the inner structure of injector head is scanned through industrial CT technology.

Experiment tests the Macro-characteristics of spray by Back-illumination, and the test simplification device is shown in Fig 1. The injector is a six holes injector of Delphi, the same injector of engine calibration.

### *2.2 Model Setting*

Spray model in this simulation contains evaporation model, breakup model, particle collision model and turbulent diffusion model. The selection of the main models is shown in Table1.

Table1 Set of Models

| *Types of Models* | *Model Select* |
|---|---|
| *Turbulent diffusion model* | k-z-f |
| *Evaporation model* | Dukowicz |
| *Breakup model* | Huh-Gosman |
| *Particle collision model* | Schmidt |
| *Spray impingement model* | Bai Gosman |

### *2.3 Constant volume vessel meshes*

The simulation calculation is consistent with the spray test condition. The boundary of the constant volume vessel is all set with boundary temperature. The temperature is 293K, the gas in vessel is air, ambient pressure in vessel is 0.1MPa.

### *2.4 Experimental and Simulation Results*

The spray penetration distance in free spray mode of simulation and experiment, as shown in Fig 2, these two are well matched.

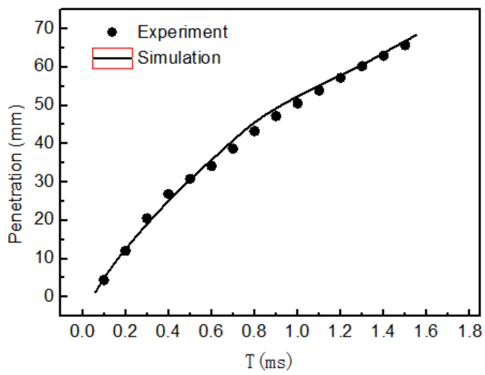


Fig 2 Comparison of experimental and simulation penetration

Table2 shows the SMD of simulation and experiment. It can be seen from this table, the SMD of simulation is higher 0.58μm than experiment SMD.

Table2 Comparison of spay particle size

| | *Experiment* | *Simulation* |
|---|---|---|
| *SMD （μm）* | 22.56 | 23.14 |

In summary, all simulation characteristic quantities of spray match well with experiment, so the spray model selection is appropriate, and the calculation of engine can be carried out.

## 3. ENGINE MODEL AND CALIBRATION

### *3.1 Engine Parameter*

The experiment engine is a four-cylinder, turbocharged GDI engine, the engine parameters are shown in Table3.

Table3 Engine parameter

| *Item* | *Value* |
|---|---|
| *Cylinder Diameter (mm)* | 82.5 |
| *Stroke(mm)* | 92 |
| *Length of Connection Rod(mm)* | 144 |
| *Compression Ratio* | 9.6 |
| *Displacement （L）* | 2 |
| *Injection Pressure (MPa)* | 5.5 |
| *Injector Nozzle Number* | 6 |
| *Injector Arrangement* | Side |

### *3.2 Meshes*

All meshes are hexahedral finite element mesh, as Fig 3 shows, the default size is 2mm. In order to improve the quality of simulation, refinements were carried on valves, valve seats and piston center, and the refinement size is 0.25mm.

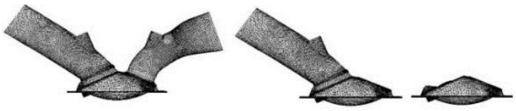

Fig 3 Engine dynamic meshes

### *3.3 Boundary and initial conditions*

A typical common operating mode of engine, running at 2000rpm and Brake mean effective pressure (BMEP) is 6bar, was studied. The initial conditions and boundary conditions setting are showed in Table4 and Table5.

Table4 Initial conditions

| *Item* | *Setting* |
|---|---|
| *Intake port pressure （Pa）* | 146965 |
| *Intake port temperature （K）* | 323 |
| *Pressure in cylinder （Pa）* | 134379 |
| *Temperature in cylinder （K）* | 1065 |
| *Exhaust port pressure （Pa）* | 134207 |
| *Exhaust port temperature （K）* | 1035 |

Table5 Boundary conditions

| *Wall* | *Temperature （K）* |
|---|---|
| *Piston top* | 500 |
| *Cylinder head* | 500 |
| *Liner* | 450 |
| *Inlet* | 400 |
| *Outlet* | 485 |
| *Intake port* | 385 |
| *Exhaust port* | 475 |

## 4. RESULTS AND ANALYSIS

In order to make a complete comparative analysis, five fuel injection schemes were set for different injection ratios and different GDI injection times combined with the test conditions. As shown in table6, Schemes 1, 2 and 3 have different injection ratios, same injection timing, Scheme 2, 4 and 5 have same injection ratio, different direct injection timings.

Table6 Spray strategy

| *Scheme* | *injection ratio GDI: PFI* | *Injection timing (°CA)* | |
|---|---|---|---|
| | | *GDI* | *PFI* |
| *1* | 100:0 | 420 | |
| *2* | 85:15 | 420 | 330 |
| *3* | 65:35 | 420 | 330 |
| *4* | 85:15 | 400 | 330 |
| *5* | 85:15 | 440 | 330 |

### *4.1 Film formation process*

When the intake valve closing, the velocity fields and distributions of film on cylinder wall and the intake port under the five injection schemes are shown in Fig 4. The red spotty particles are the distribution state of fuel droplets in the cylinder, and the blue layer is the spatial distribution of fuel film thickness.

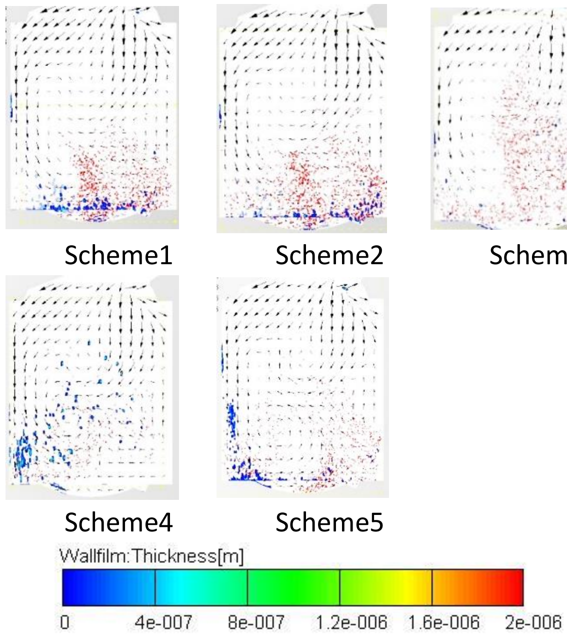


Fig 4 The velocity and wall film thickness distribution in cylinder when inlet closing（549° CA）

Fig 4 shows that in Scheme1, the fuel film is distributed on the top of the piston, the cylinder wall opposite the inlet port and the intake valve. Among them, most of the fuel film is distributed on the top of the piston, and after the intake valve closing, some fuel still adhere to the top of the piston even under the action of air entrainment and film is formed, and very small amount of film is formed on the intake valve caused by the air flow in cylinder. In addition, it can be seen that the increase of PFI injection ratio leads to the formation of a large number of fuel film on the intake port wall and the back of the valve, which indicates that the film thickness is positively correlated with the PFI ratio, and the film thickness increases with PFI ratio increasing.

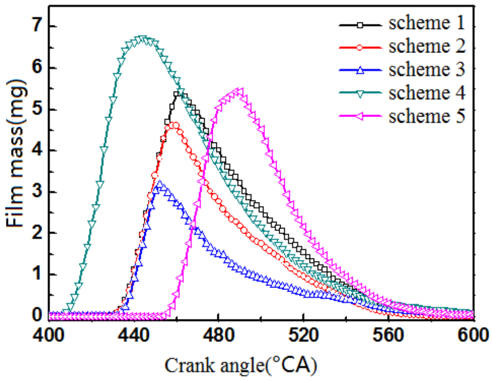


Fig 5 Film mass in cylinder

Fig 5 is fuel film quality curve on engine cylinder wall. The quality curves of film in cylinder all show single peak distribution. It can be seen from the change of fuel film peak value in Scheme 1 to 3 that the peak quality of fuel film decreases with the decreasing of GDI injection ratio. Compared with Scheme 1, when the PFI injection proportion increased to 15%, the peak mass of the fuel film in the cylinder decreased by 0.77mg, that is 14.3% of scheme 1. When the PFI injection proportion is 35%, the peak mass of the wall film in cylinder is 3.17mg, which is equivalent to 60% of Scheme 1.

The peak time of fuel film is pushed back with the direct injection timing delay, and the peak quality of fuel film decreases first and then increases with the delay of timing of direct injection. In these three injection timing schemes, injection at 420 ° CA has the lowest peak fuel film quality, injection start at 400 ° CA has the highest peak fuel film quality. Since 360 ° CA to 540 ° CA is the piston down phase, when the injection timing in advance, the spray is near to the top surface of the piston, and it's benefit to film formation, so injection timing at 400 ° CA has highest fuel film peak quality.

### *4.2 Film influences on soot emission*

Fig 6 is the soot mass fraction distribution under different injection strategies, the soot concentrated in the intake side of the cylinder, which is caused by the high concentration of the mixture and the low temperature on the inlet side during combustion. Changing the GDI injection timing, when inject at 420 ° CA the soot mass fraction distribution area is minimum, the soot mass fraction distribution area will increase when GDI fuel injection timing in advance or delay.

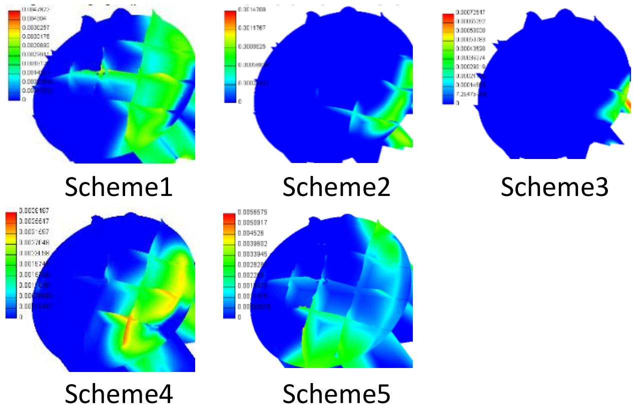


Fig 6 Soot mass fraction distribution in cylinder

Fig 7 shows the soot formation process in cylinder. The trend of soot quality of simulation and test matches well, the result also indirectly verifies fuel collision and fuel film evaporation of simulated process. With the decreasing of GDI proportion, soot mass fraction peak decrease, peak moments delay, the final soot mass fraction lower.

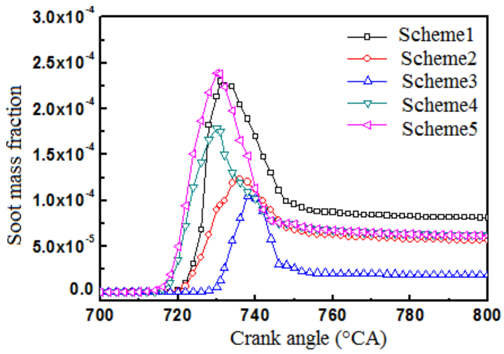


Fig 7 Soot generation process in cylinder

Due to GDI proportion decreases, the fuel directly injected into the cylinder reduces, fuel impinge the wall and wall film quality decrease, at the same time film thickness and surface area of film reduces, it makes thick regional volume decreases and lead to soot formation decreases.

## 5. CONCLUSIONS

Under study conditions, the mixture uniformity index decreases with the increase of peak wall film mass. Film is formed in the exhaust side, in the effect of tumble in cylinder thicker mixture is formed on the intake valve side at ignition time, soot concentrate in the region of relatively rich mixture.

Film mass and film distribution area decrease first and then increase with the delay of GDI injection time. Soot emission decreases first and then increases with GDI injection timing delay. Appropriate advance direct injection fuel injection timing can reduce the fuel impingement and improve the mixture uniformity and soot emissions.

**ACKNOWLEDGEMENT**

First and foremost, I would like to show my deepest gratitude to my advisor, Dr. Qin Jing, who has provided me with valuable guidance in every stage of the writing of this thesis. I shall extend my thanks to and Dr. Liang for all his kindness and help. I’d like to thank Dr. Pei and all my teachers who have helped me to develop the fundamental and essential academic competence. Last but not least, I' d like to thank all my friends for their encouragement and support.

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